Advances in state estimation for lithium-ion batteries

Matthias Vetter, Stephan Lux, Peter Raab

Fraunhofer Institute for
Solar Energy Systems ISE

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Agenda

- Introduction
- Motivation in "non-consumer" applications
- Battery management systems
- The problem of state estimation
- Principle of particle filters
- Dual particle filter for state of charge and state of health estimation
- Results
- Conclusions

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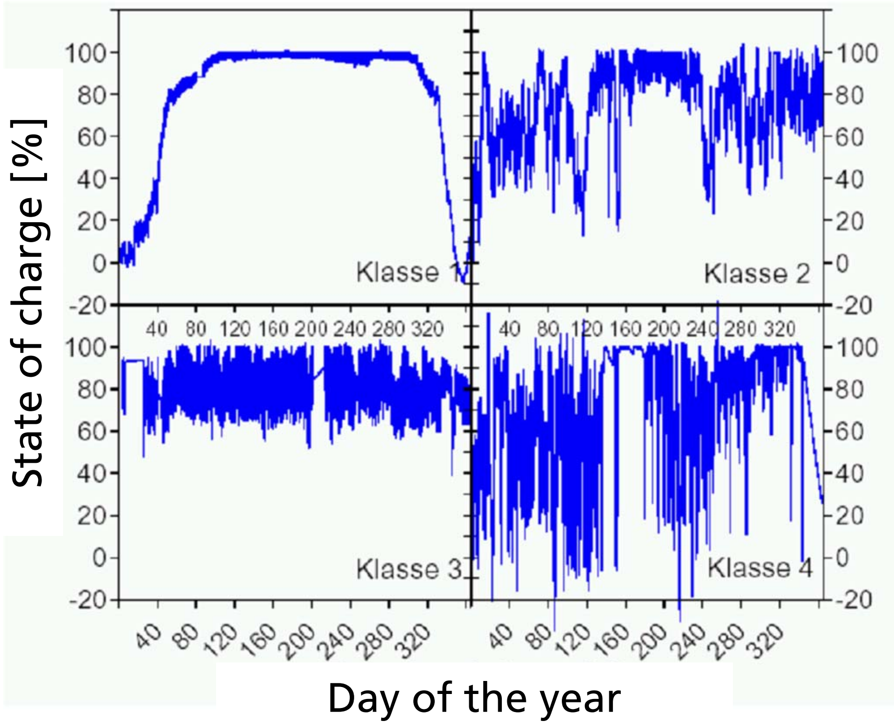
Motivation in non-consumer products

- Fluctuating renewable resources
- Frequently full charging not secured
- Partial cycling at different state of charge levels
- Precise state algorithms necessary for an optimized energy management

Example:
Storages in PV off-grid systems
Classification of operating conditions



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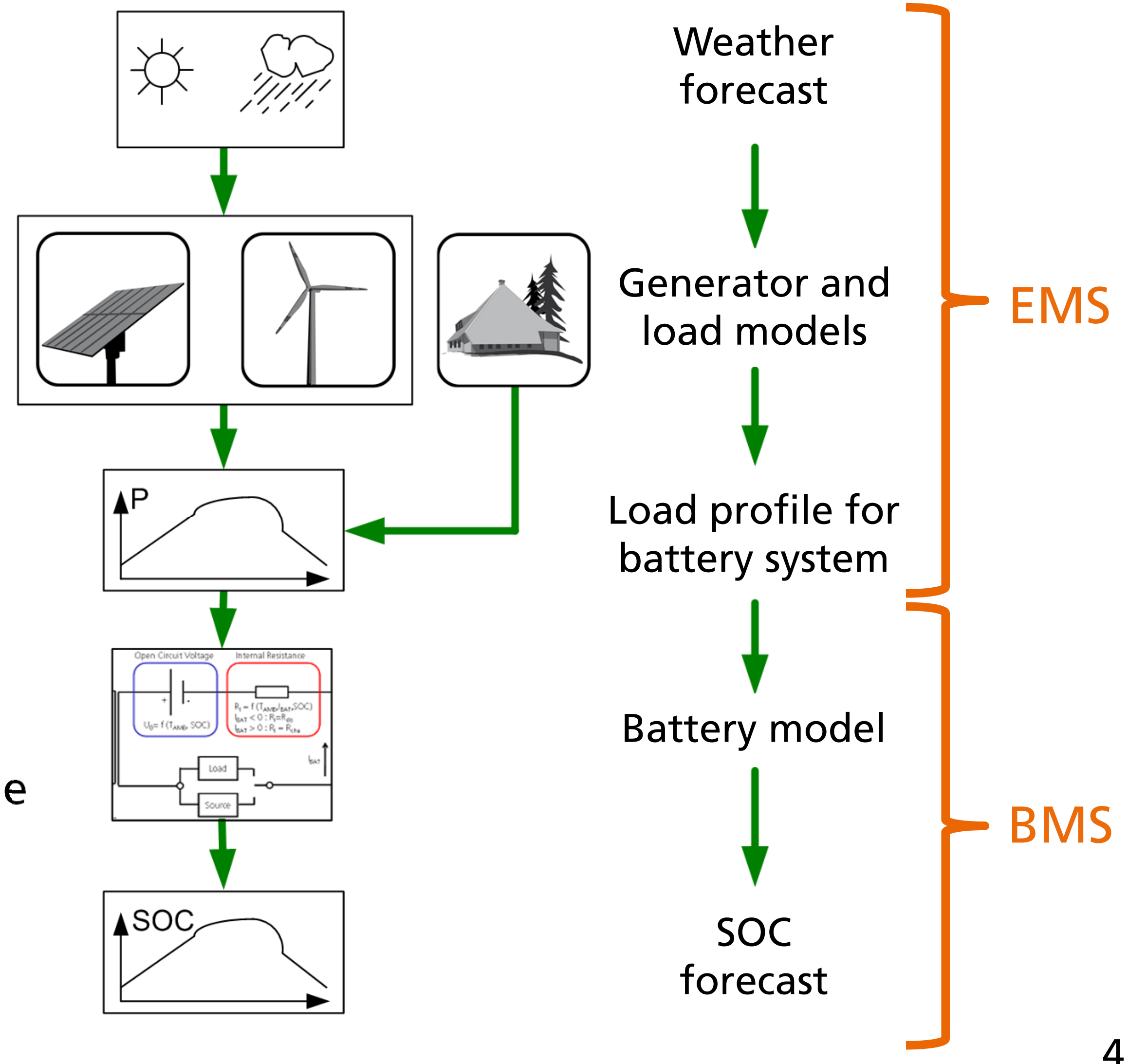
Example power supplies: Smart battery management as part of an optimized energy management

- Communication interface between EMS and BMS
- Model based energy management
  - Load and generation management
  - Optimized operation of battery system
  - → Control of energy fluxes
- Model based battery management
  - SOC prediction in dependence on load profile forecast
  - Efficiencies in dependence on load profile forecast
  - Information on aging



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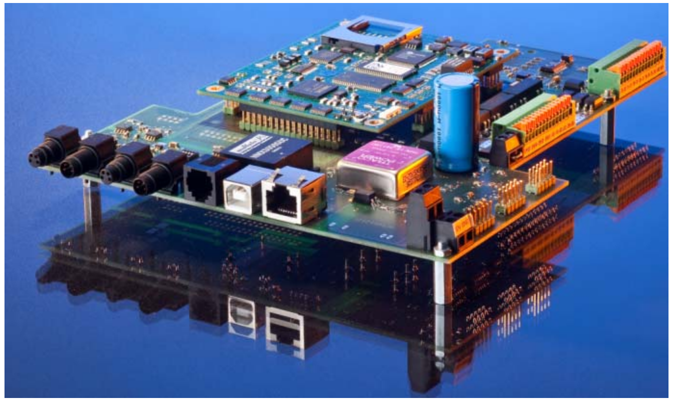
Battery management systems
Motivation and objective

Objective:

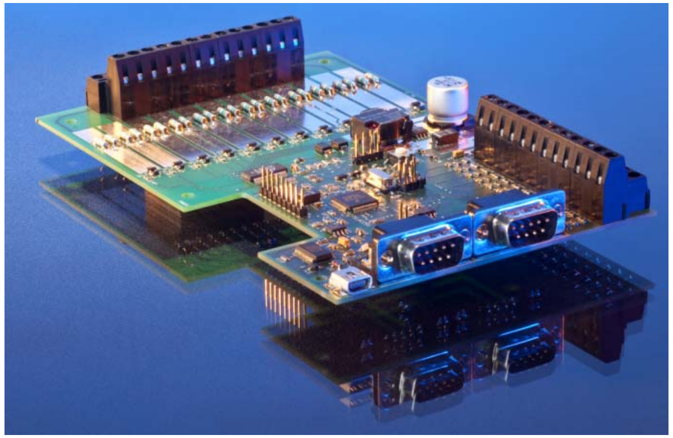
Lithium-ion cells have to be monitored and controlled, important issues are:

- Safety (e.g. overvoltage/undervoltage detection)
- Cycle and calendar life time
- State estimation
- Temperature/voltage monitoring
- High efficiency (well suited cell balancing, low energy consumption of the BMS)

Objective reachable
with high end battery management systems



Central management unit



Module management unit

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Battery management system
Overview and function blocks

State estimation
- SOC
- SOH
- Other states (optional)

Control system
- Actuators and switches
- Battery models
- Load management
- Energy management (optional)

control layer

Error management
- Safety for cells

Battery **M**anagement **S**ystem

Thermal management
- Thermal battery models
- Thermal control

safety layer

Measurement and monitoring
- Cell voltages
- Temperature
- Current

Communication
- Internal
- To external components

functional layer

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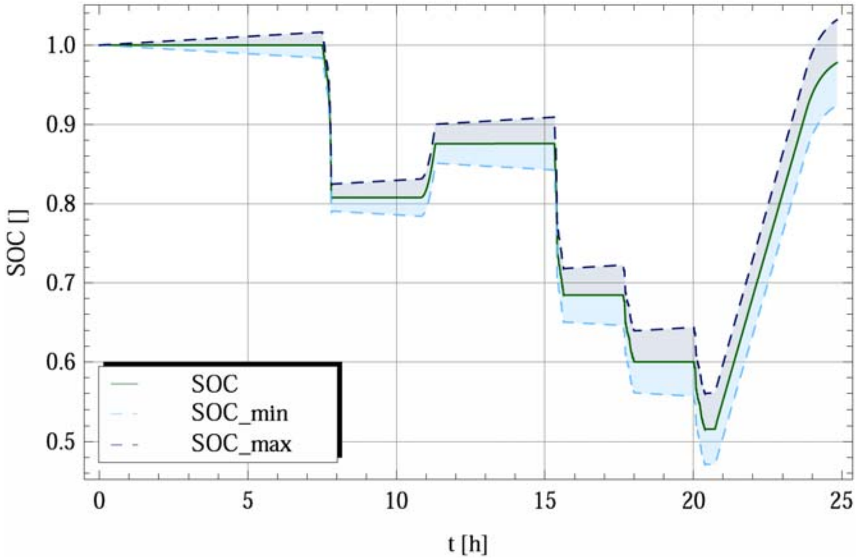
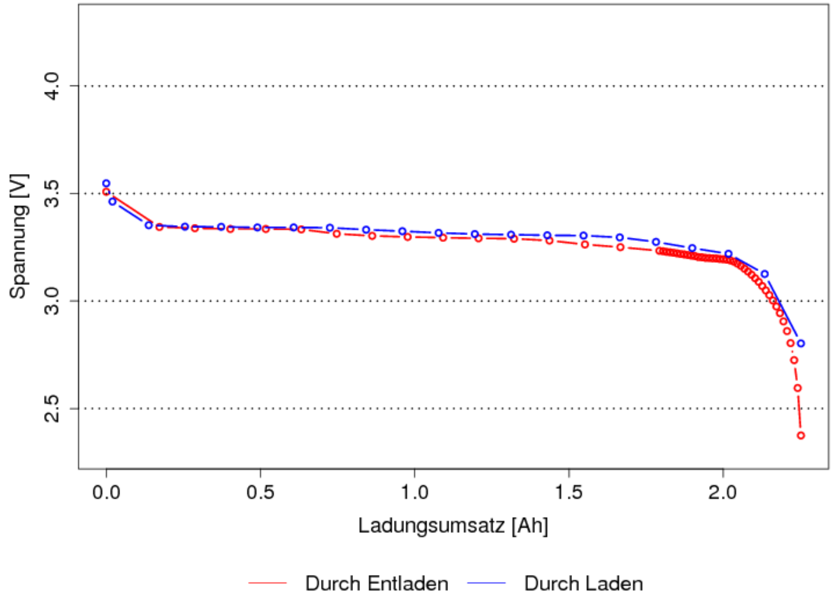
The problem of state estimation

- Inner states of the batteries need to be known for e.g.
  - Prognosis of the remaining run-time in an application
  - Estimations of power capability
  - The point in time for replacing the batteries
- Inner states cannot be measured directly:
  - Inner resistance
  - State of charge (SOC)
  - State of health (SOH)
- Procedures shall only use simple measurement values like terminal voltage, current and temperature

Example: State of charge estimation

- Ah counter: Integration of measurement errors
- Most conventional approaches:
  - ➢ Use of some kind of OCV correction in combination with Ah counting
    - → Recalibration of the SOC value via OCV consideration needs resting phases
- Flat OCV characteristic with hysteresis for $LiFePO_4$





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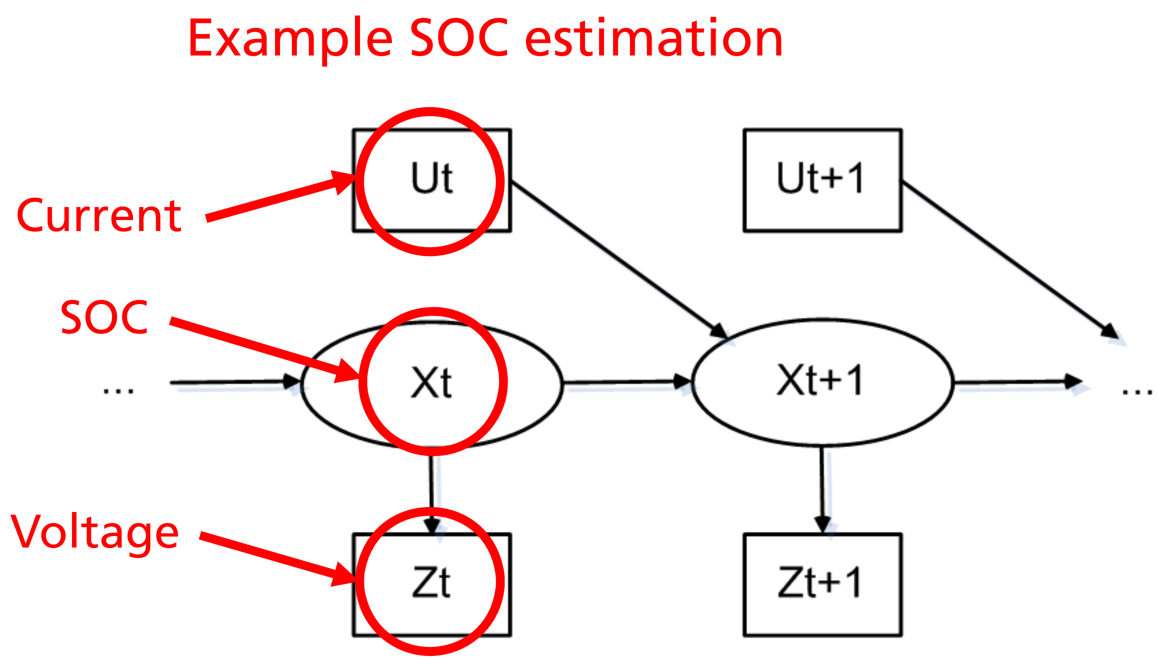
Introduction to Bayesian filters

- Assumption of a Markov chain:



- It is imperative:
  - Input *U* and Output *Z* are stochastically independent
  - If X_t and U_t are known, then X_{t+1} will be independent from all previous states $X_1,\ldots,X_{t-1}$
  - U_t is statistically independent from $X_1,\ldots,X_t$ and $U_1,\ldots,U_{t-1}$
  - If X_t is known, Z_t will be independent from all other variables
- Bayesian filtering equation: $P(x_t) = \eta^{-1} P(z_t \mid x_t) \int P(x_t \mid x_{t-1}, u_{t-1}) P(x_{t-1}) dx_{t-1}$
- A typical filter of this family is the Kalman filter

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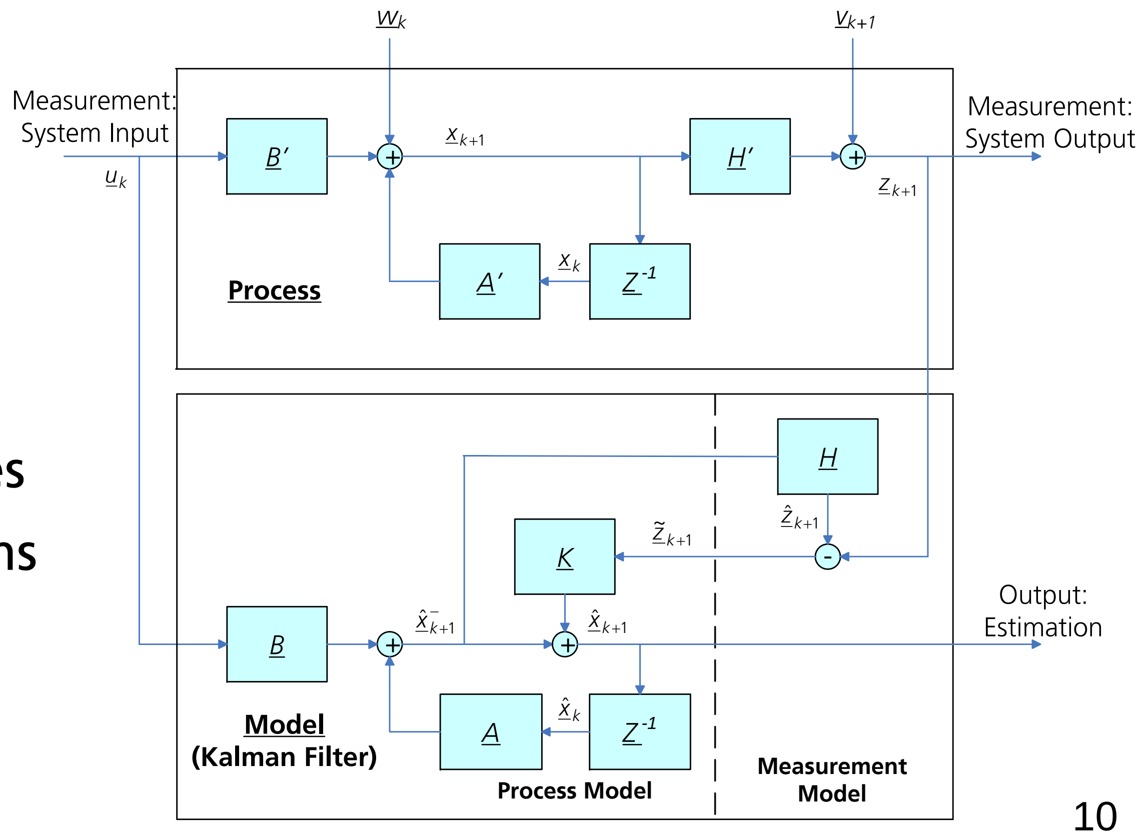
Kalman filter approach
Example: State of charge determination

- Recursive stochastic state estimator
- More insensitive against measurement errors
- No resting phases necessary for recalibration of SOC
- Fast identification of starting values
- Improved performance for aged batteries

Drawbacks:

- Optimal estimator only for processes with Gaussian noises
- Suitable only for linear systems
  → For non-linear systems: Extended or Unscented Kalman Filter



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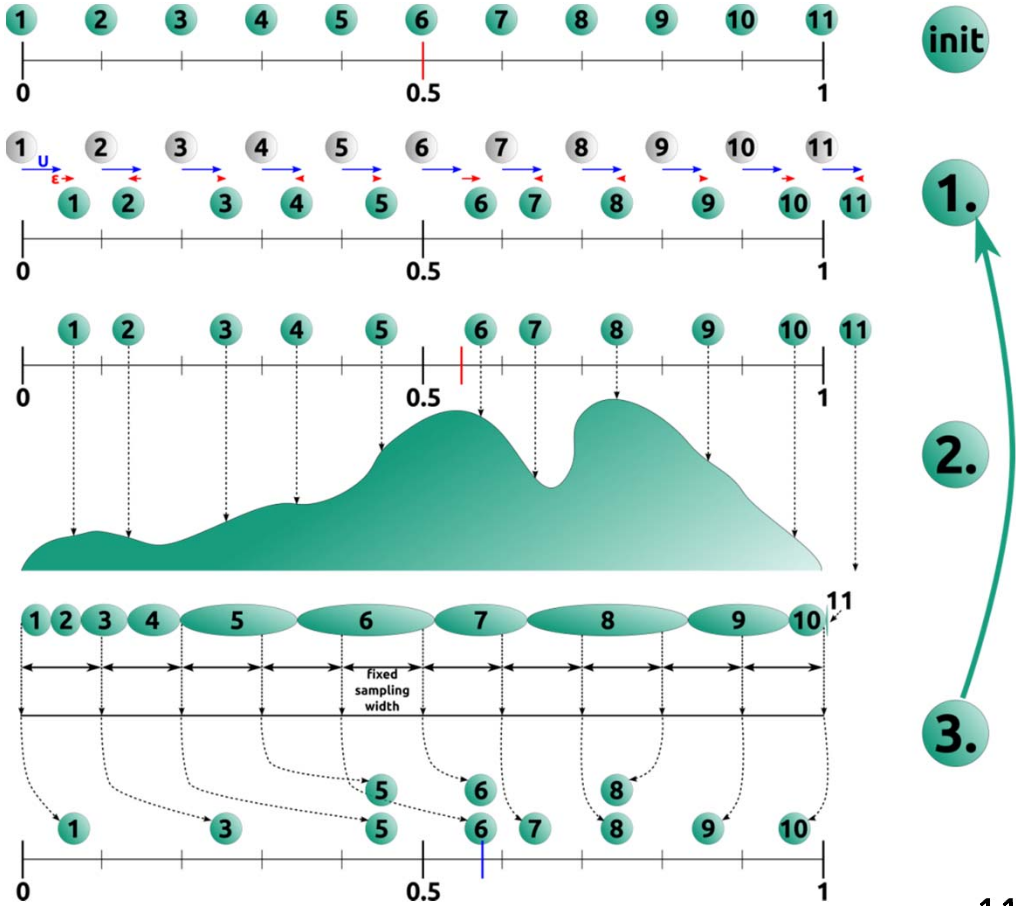
Particle filter approach
Introduction

- All probability density functions are approximated by samples (Monte Carlo method)
- Offers possibility to deal with any kind of distribution by approximating the respective probability density function by a set of particles or samples
- Offers possibility to use multimodal distributions



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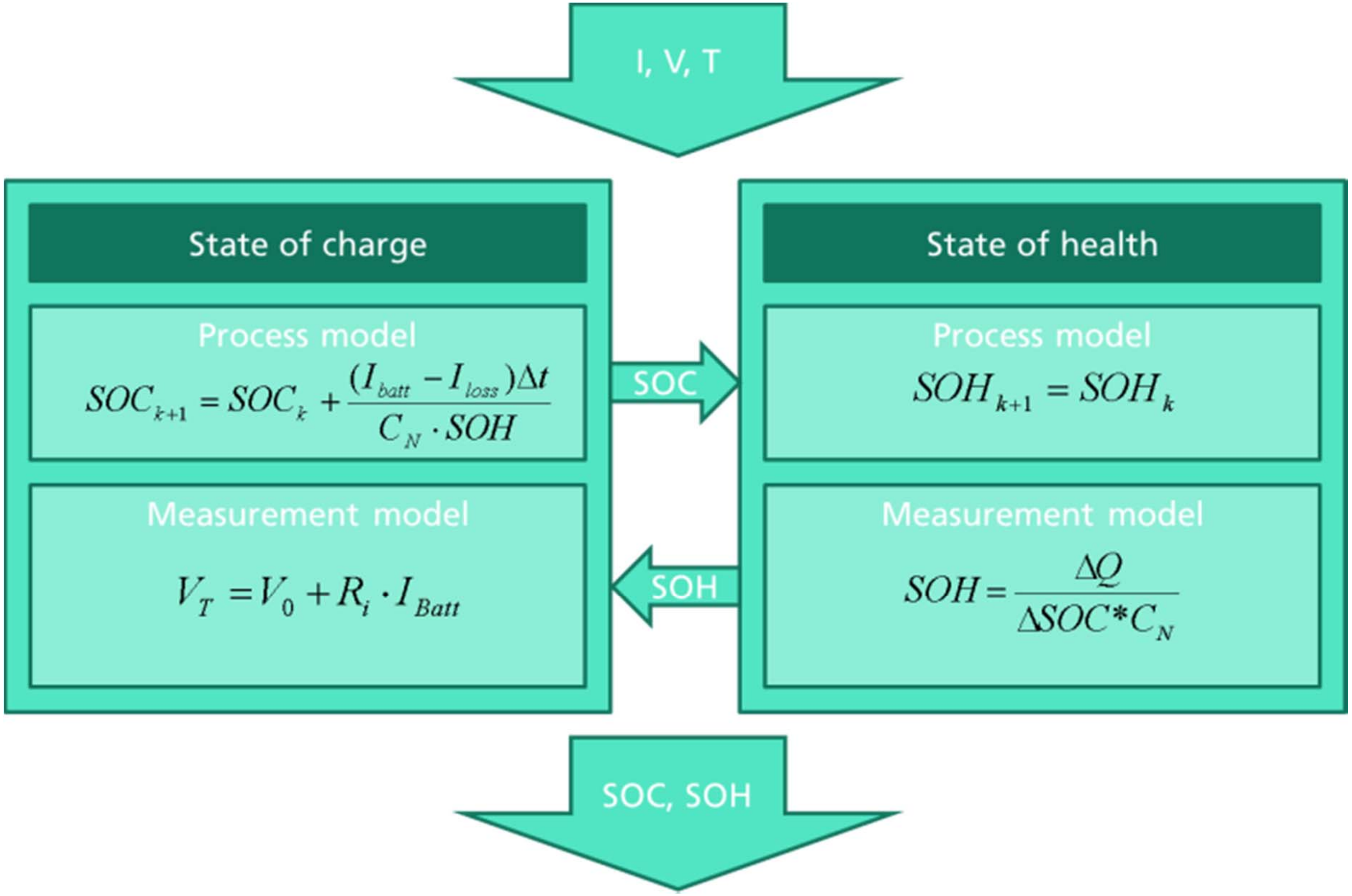
Dual particle filter
State of chare and state of health estimation



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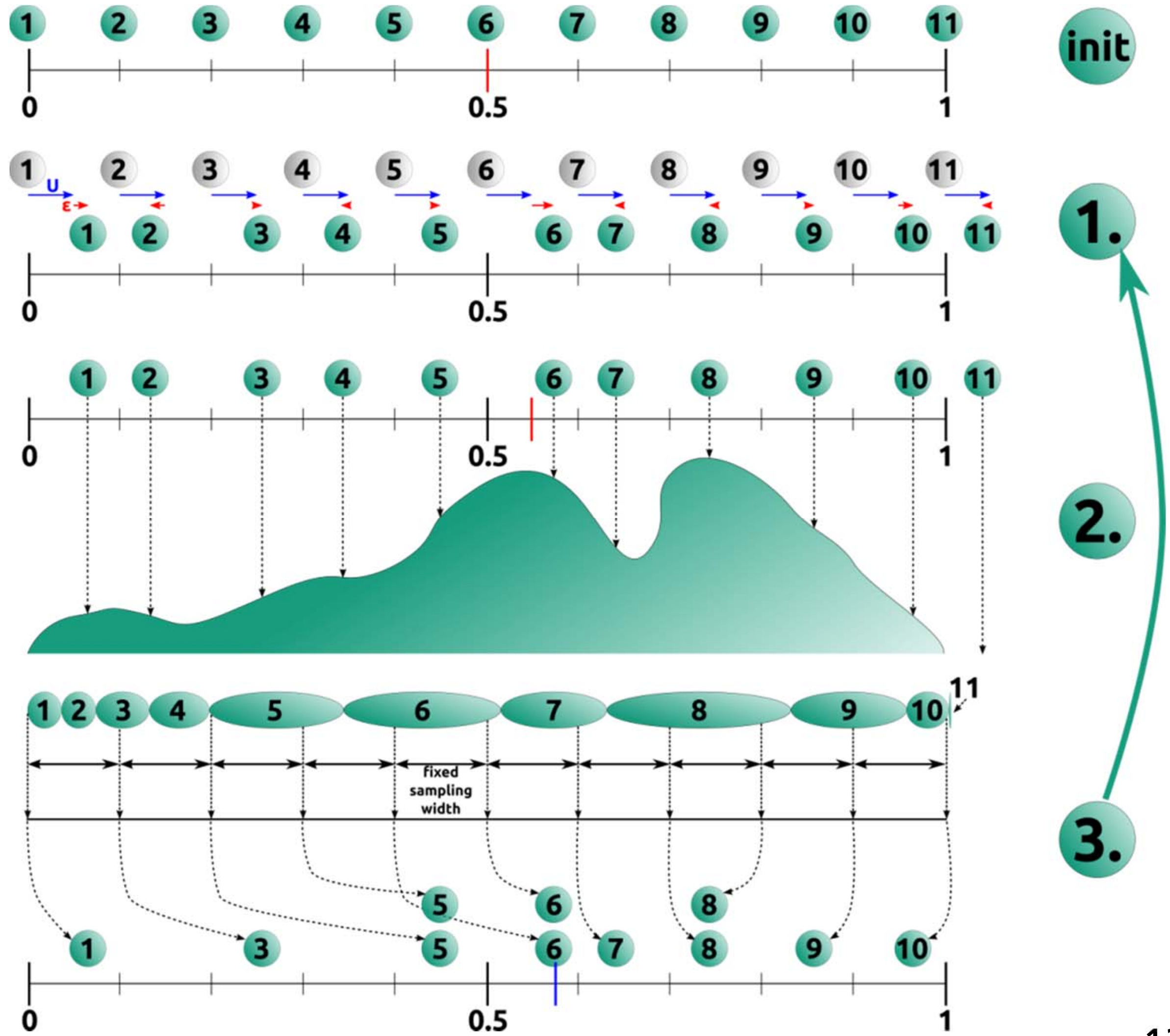
Particle filter
Example "State of Charge" estimation



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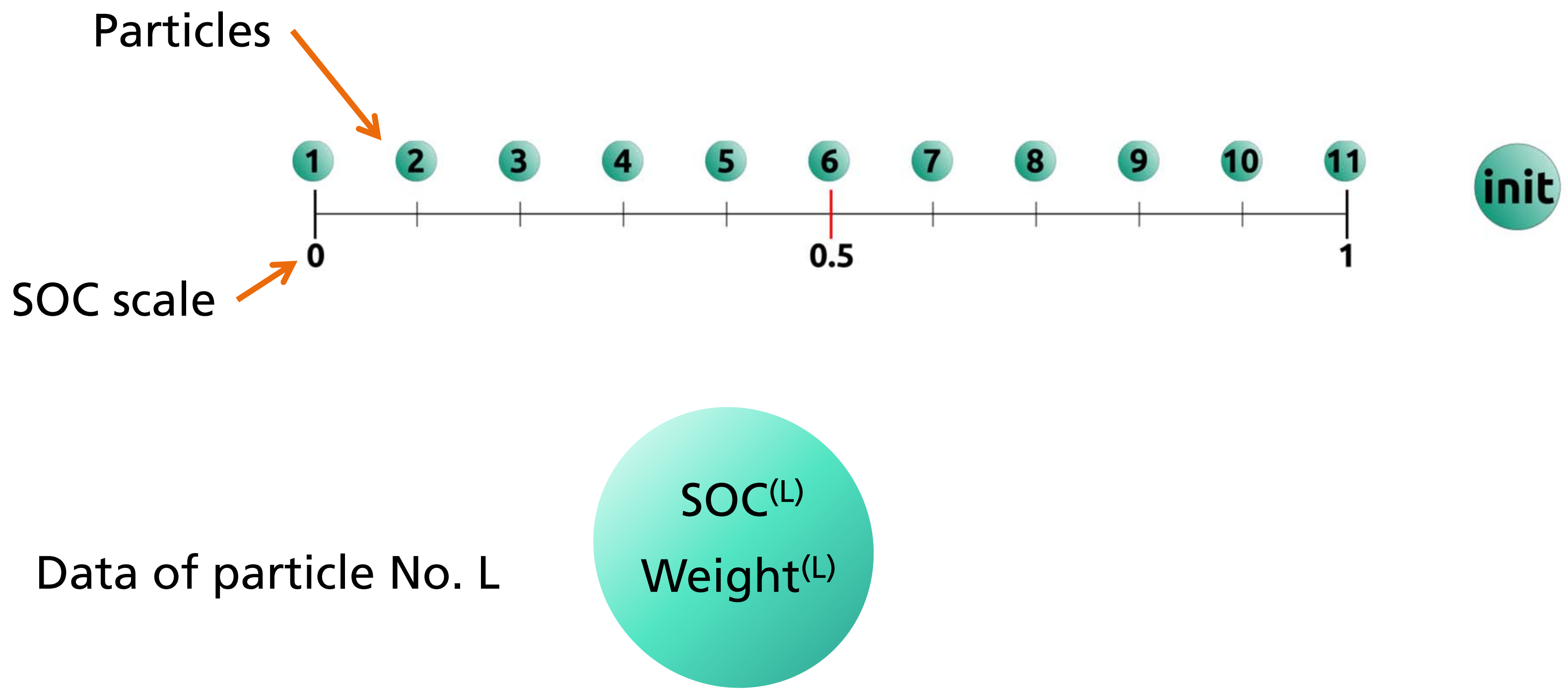
Particle filter
Example "State of Charge" estimation

Initialization: No preliminary information

→ SOC unknown

→ Particles have been uniformly distributed over the entire SOC scale



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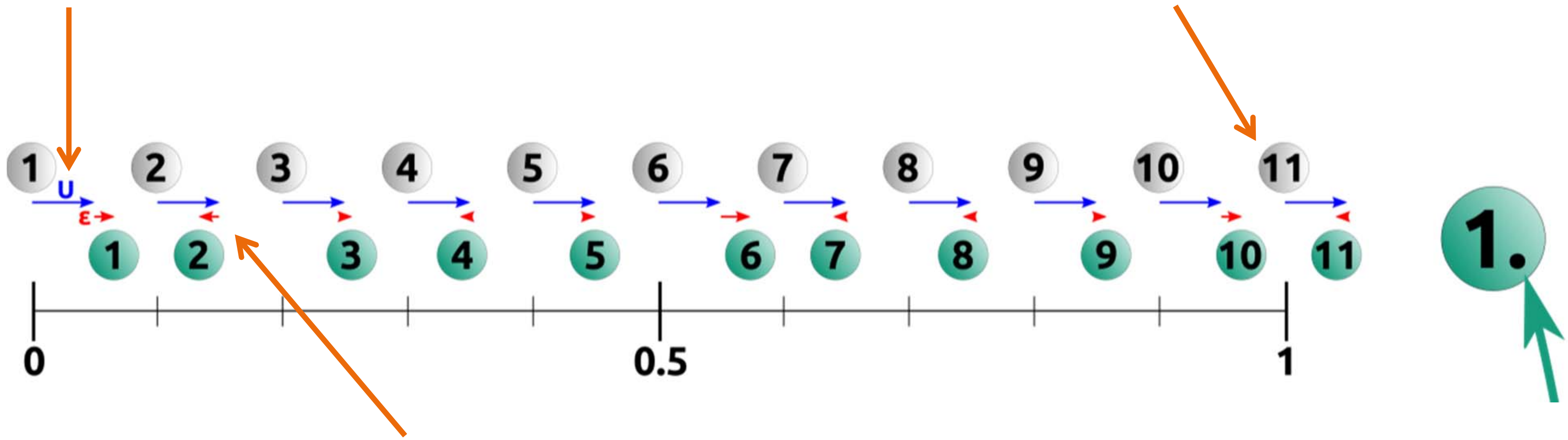
Particle filter
Example “State of Charge” estimation

1. Step: Use of the process model, diffusion

Deterministic component
Δt * I → Ah counting

Grey: SOC-“position“ of the initial step or the previous step



Stochastic component
Process noise

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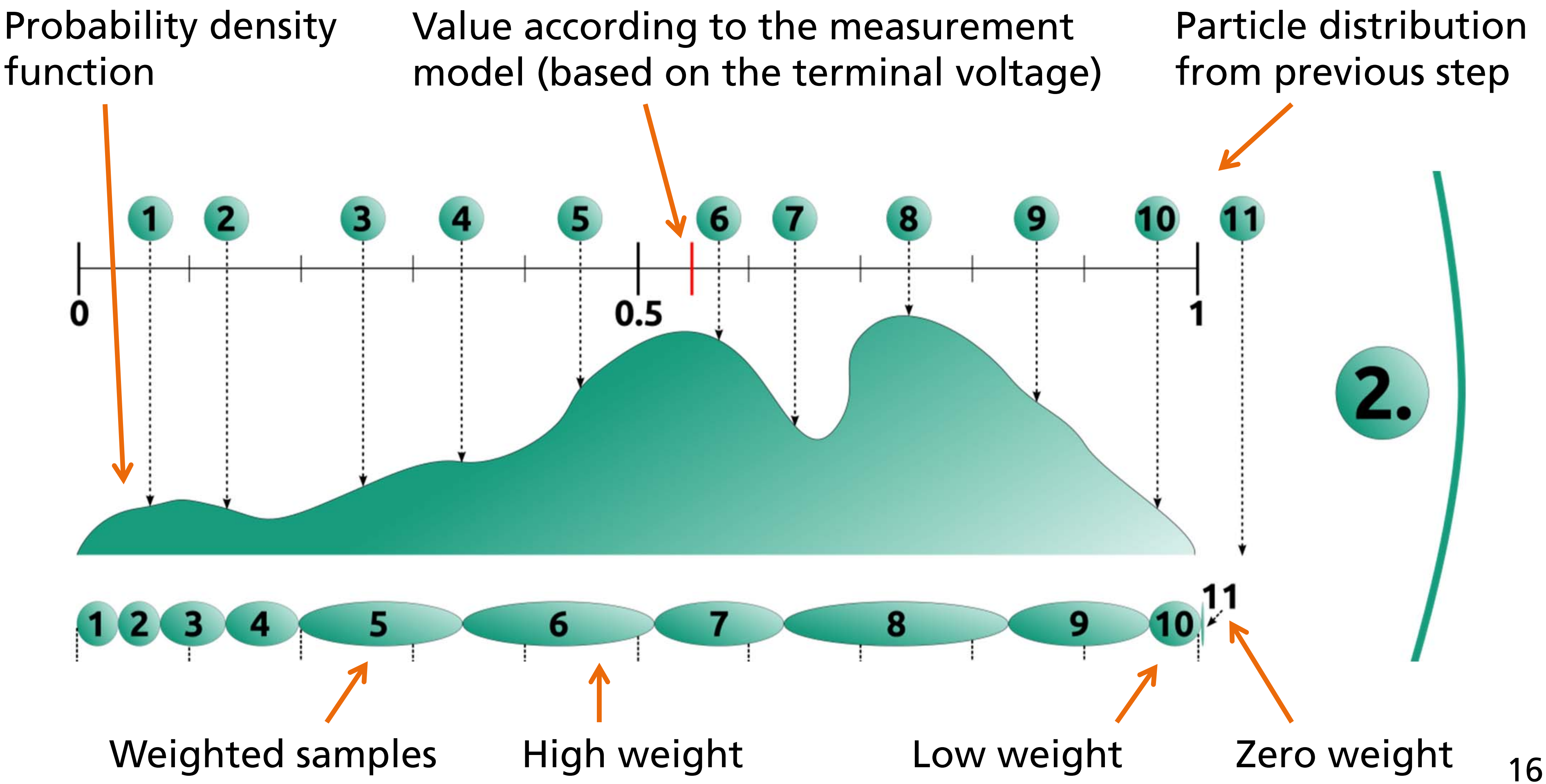
Particle filter
Example "State of Charge" estimation

2. Step: Use of the measurement model, weighting



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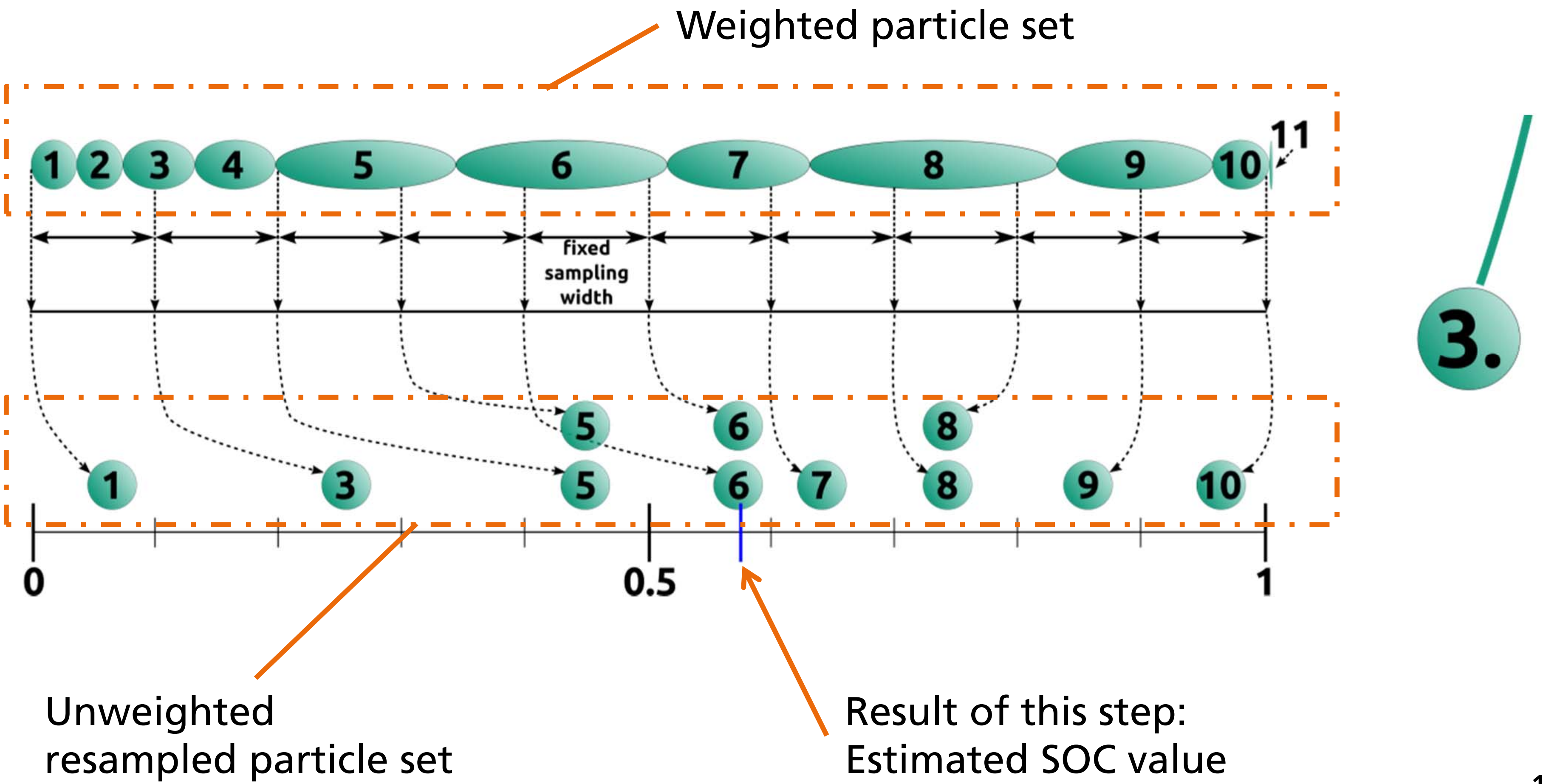
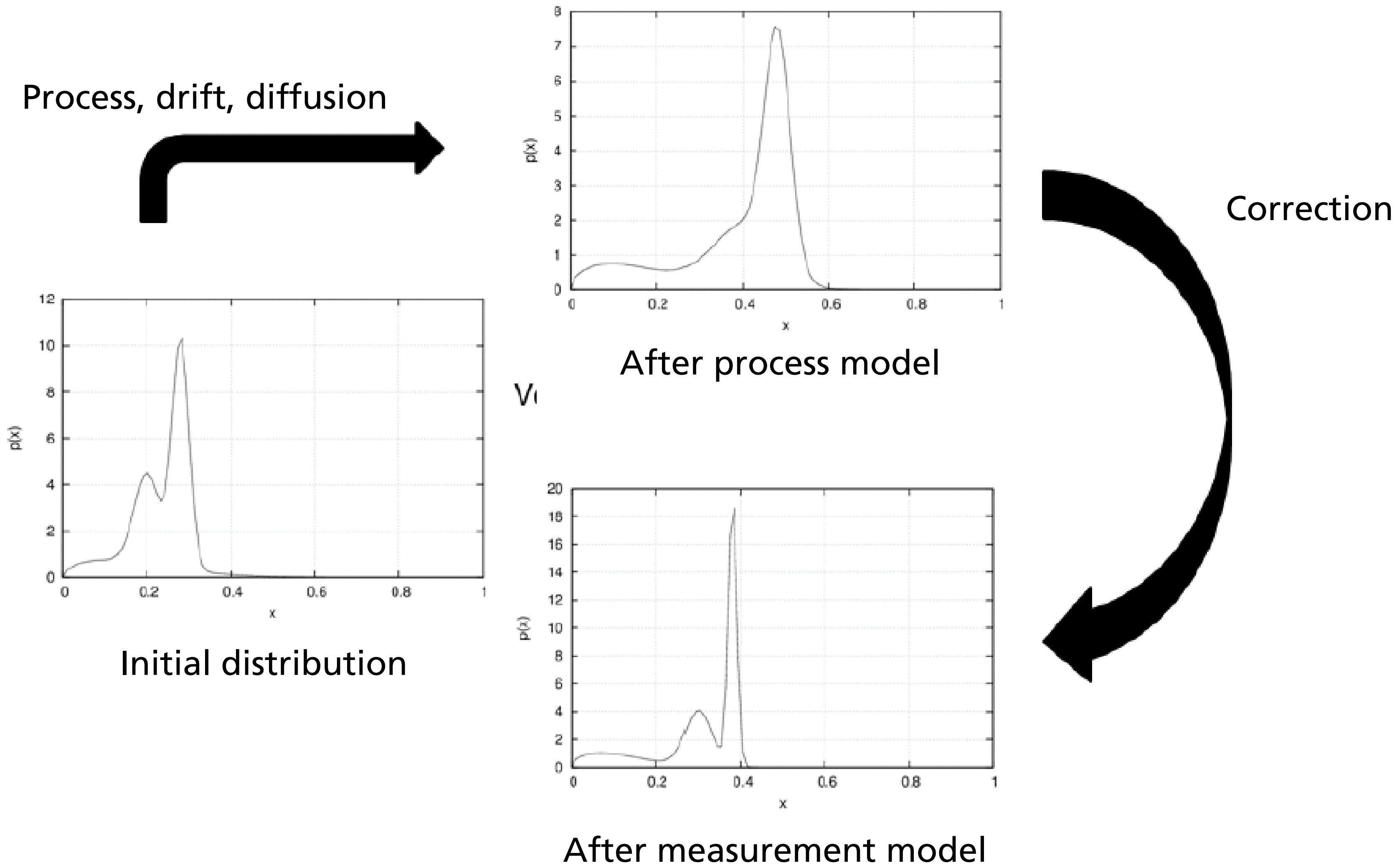
Particle filter

Example "State of Charge" estimation

3. Step: Low variance resampling

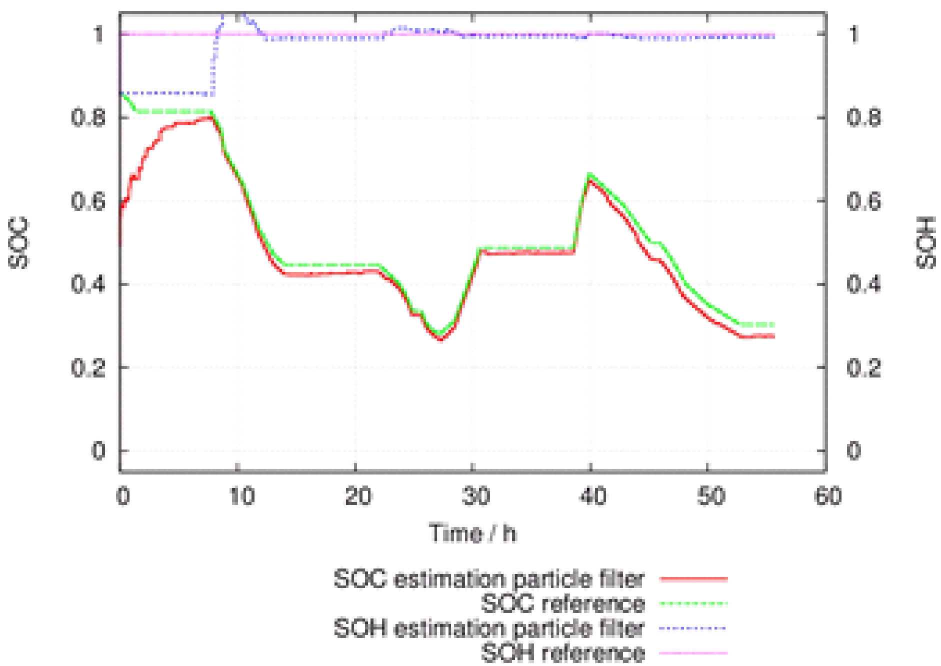


Particle filter
Evolution of probability density function

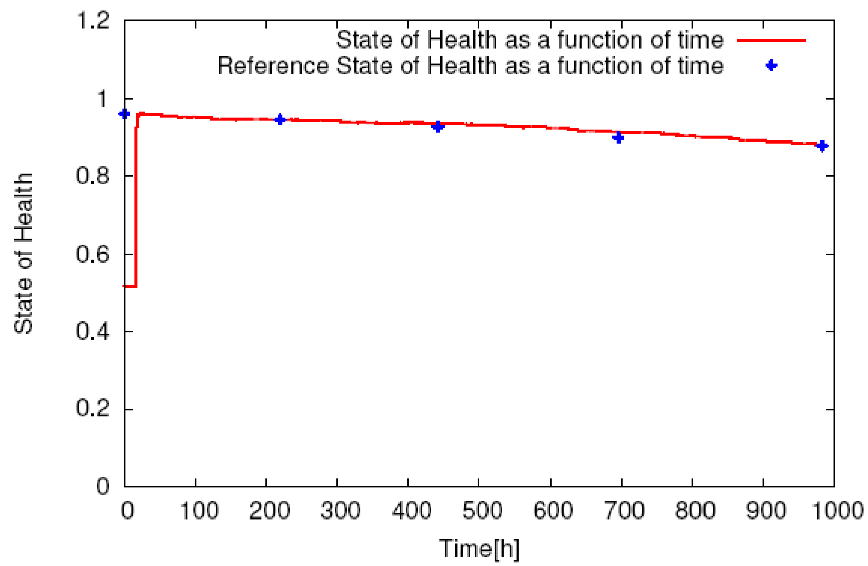


Particle filter
Results

Stationary PV application
State of charge and state of health for $LiFePO_4$

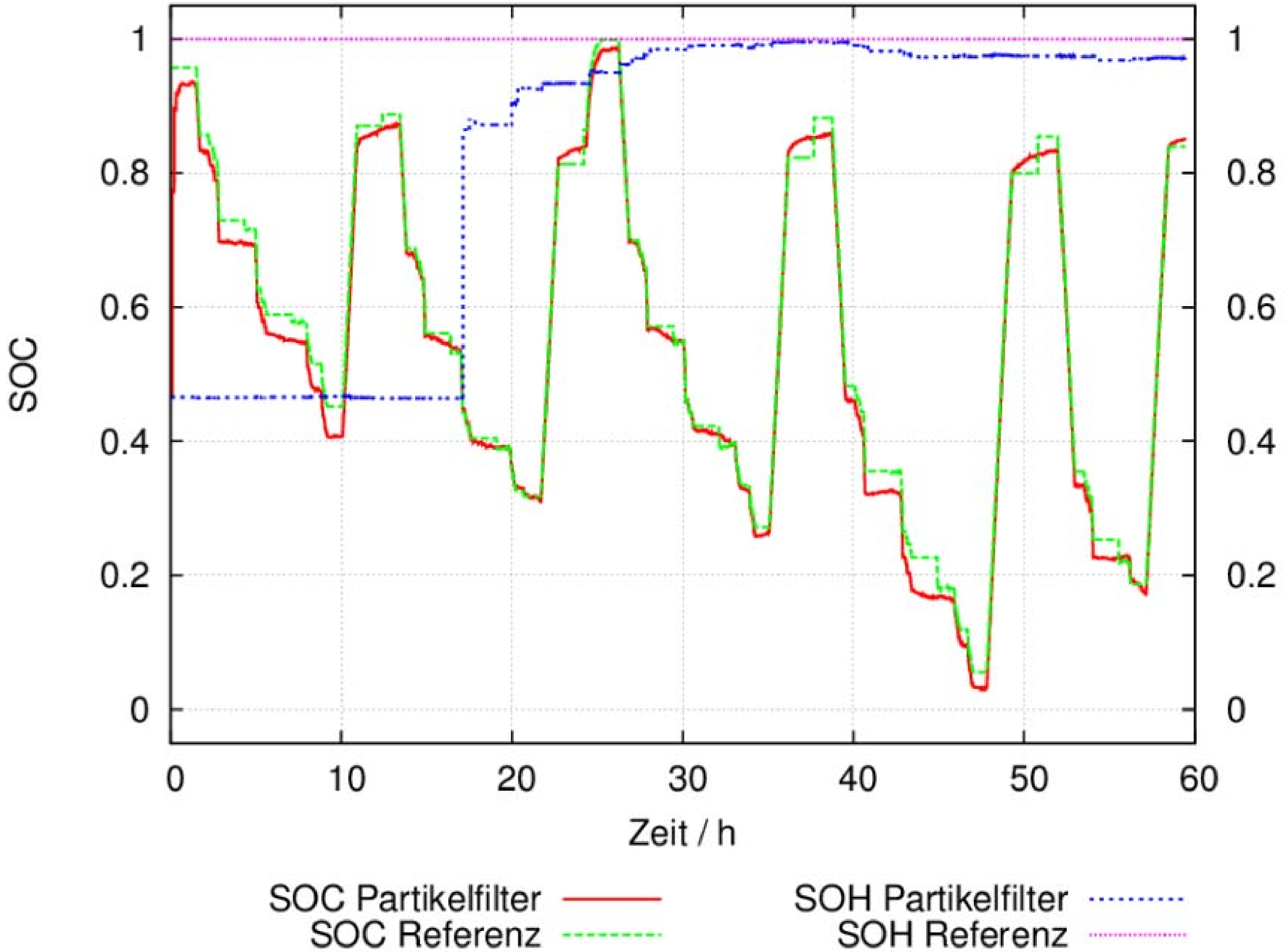


"Long-term" testing
State of health for NMC

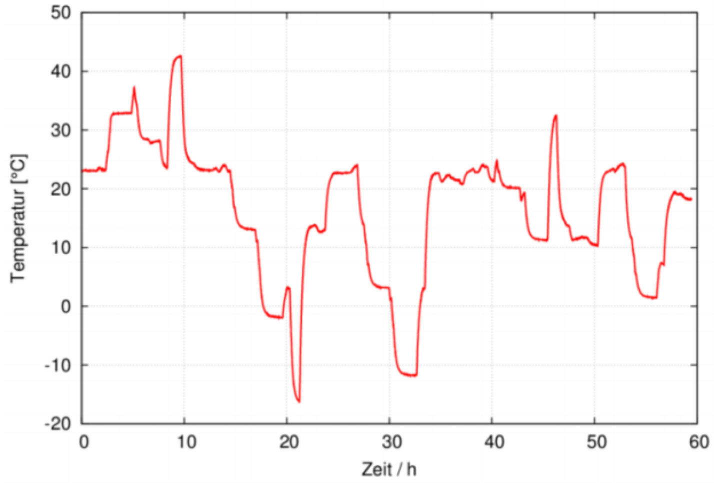


Particle filter
Results

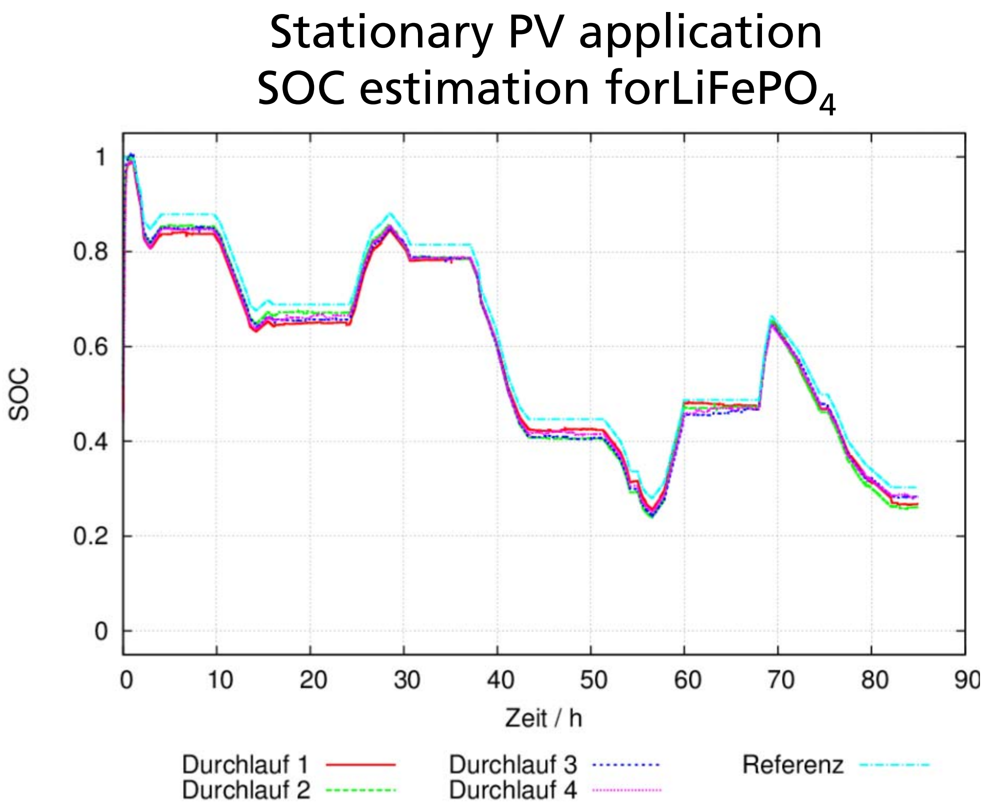
EV application
State of charge and state of health for NMC

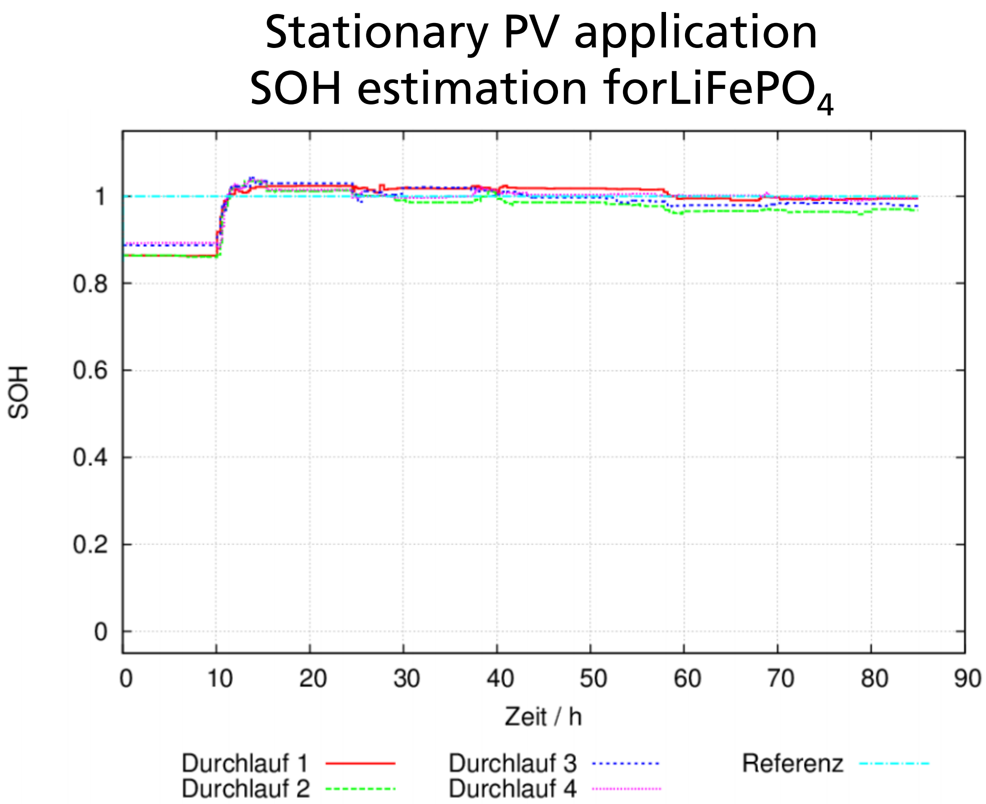


Imposed temperature



Particle filter
Results – Filter noise





Conclusions

- State of charge and state of health estimation very important but also sophisticated task for *nearly* all battery applications
- Particle filter for state of charge and state of health estimation with the following features:
  - **Precision:** Finds “true“ value with minimal variation
  - **Speed:** Sufficiently fast to cope with PV as well as EV profiles
  - **Flexibility:** Able to cope with different initial values and temperature profiles
- Due to low computational efforts it can be implemented very well on small scale microcontrollers of battery management systems

→ Particle filter is a very flexible and reliable tool for estimating inner states of batteries

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Thanks for your attention !!!

Contact:
matthias.vetter@ise.fraunhofer.de

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